On the Joint Optimisation of Radio Access and Backhaul Networks

(Invited Paper)

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***Abstract*—The distinction between the radio access network and the backhaul network is disappearing with emerging advanced features. The backhaul is invading the radio assess spectrum to enable wireless in-band connections and the radio network is overlapping with the transport network through cloud processing and distributed functions. As such, it is of pivotal importance to approach the optimisation of the radio and transport networks jointly to avoid suboptimum operation and problem shifting. In this work, we present a critical analysis of the motivations, state-of-the-art advances, and potential benefits and challenges of joint RAN/backhaul optimisation.**

I. Introduction

Traditionally, the radio access network (RAN) and transport network (or backhaul BH) have been considered as separate entities of radio cellular networks. In many cases, these are owned and/or managed by different companies and allow different levels of network sharing. Thus, the 3rd Generation Partnership Project (3GPP) still considers the BH and RAN as two distinct network parts and is only concerned with standardising the respective interface. However, with the emergence of next generation mobile networks (NGMNs), this distinction is slowly vanishing and the overlap between RAN and the BH is increasing. The centralised-RAN or cloud-RAN (C-RAN), for instance, consists of redistributing RAN functions, which are traditionally found in base stations (evolved Node-B or eNB), towards a cloud-operated central processor (Base band unit or BBU) and leaving only the radio functions at the remote radio unit (RRU). The BBU forms a shared pool to all connected RRUs, revolutionising the concept of traditional eNB and puts forward the disruptive concept of a virtual-eNB which is composed of RAN and BH segments (referred to as fronthaul) to connect its distributed parts. The C-RAN architecture addresses many challenges from the radio perspective, however, the resulting stipulated performance requirements in the fronthaul may become crippling. As such, designing, operating, and optimising a network employing C-RAN demands a joint RAN/BH approach. In-band backhauling is another example of blurry RAN/BH demarcation. It is based on the reuse of radio access spectrum to backhaul eNB's or RRU's, employing beamforming antennae. In this case, the BH network occupies parts of the RAN spectrum and is no longer a distinct network section.

An aggressive joint radio access and BH design was introduced by the BuNGee project earlier in 2010-2012, promoting the benefits of such joint operation for the purpose of optimised performance and efficiency [1]. The outcomes of the BuNGee project were used in the ETSI (European Telecommunications Standards Institute) technical reports on Broadband Radio Access Networks (BRAN) [2], [3]. iJOIN's view of network evolution towards 5G is that "...blurring borders between access and the BH networks require a joint design of both " [4].

In this work, we present a state-of-the-art survey of recent advances in joint RAN/BH optimisation as detailed in Section II. The benefits and challenges of joint RAN/BH optimisation are discussed in Section III through an in-depth analysis of the user-centric backhaul (UCB) concept. The paper is concluded in Section IV.

II. State-of-the-art advances on joint RAN/backhaul optimisation

It is commonly agreed that the joint optimisation of the RAN and BH sections of the network is inevitable in future networks. This has translated into a surge in research and publications that address different aspects of the joint optimisation challenge. These can be classified in two distinct categories: RAN/BH awareness and joint RAN/BH functional design, as proposed in [5].

Examples of RAN/BH awareness are many, such as backhaul aware resource allocation (e.g., [6]) and cell association (e.g., [7]). Authors in [8] use a centralised optimisation mechanism to adjust the cell range extension offset, in order to minimise the mean network packet delay. Another article addresses the issues of BH latency and resilience through a BH-aware user association that aims at improving quality of service (QoS) while balancing the network load [9].

On the other hand, joint functional design consists of network-wide functionality such as global energy efficiency optimisation (e.g., [10]) or spectral efficiency maximisation (e.g., [11]). iJOIN in [12] present a novel architecture for next generation systems in which data and control planes are decoupled. RRUs are used for data offloading, but an anchor point (that ideally overlooks several RRUs) is dynamically configured for the control plane. A network controller node, that communicates with the VeNB controller and the BH, finds an adequate anchor point for each incoming UE, based on QoS. It also determines the BH optimal route based on the anchor point, QoS, as well as the current network status, taking into account energy consumption in the RAN and BH, congestion, and requirements of the VeNB.

A different perspective is offered in [13] which proposes in-band backhauling and optimised resource allocation scheme that maximises user throughput. A user-centric backhaul (UCB) scheme is proposed in [14] which optimises the user-cell association process by taking into consideration the BH constraints, RAN conditions, and user's content and requirements. Authors in [15] propose a fuzzy Q-learning optimisation approach for controlling discontinuous transmission of small cells. They aim to jointly minimize the power consumption of the RAN and BH while respecting users' quality of experience (QoE).

Fog Radio Access Network (F-RAN) is an evolution of C-RAN in which edge devices are assumed to perform some baseband processing functions locally in order to alleviate the fronthaul stipulated performance [16]. Equipping F-RAN with distributed storing capability can greatly reduce the delay perceived while preserving some benefits of C-RAN. In another F-RAN related work, [17] proposes a green-motivated joint optimization algorithm of RRU selection and load-balancing oriented clustering by taking the operational power and BH capacities into account.

III. Challenges and potential of joint RAN/BH optimisation

A. The burden and opportunities of diversity in NGMNs

The NGMN BH network is a major challenge due to the pervasive extensions required to cater for fast-spreading small cells. Furthermore, the highly exigent performance requirement of the expanding BH are not the least challenging. Optical fibre networks can offer this grade of service but are not widely available. Moreover, the inherent lengthy and cumbersome process of laying new fibre is inhibitive in comparison with the speedy cell deployment. Wireless technologies in the millimetre-wave bands, especially the E-band (70/80 GHz) and D-band (141-174.8 GHz), are close contenders with expected performance in par with fibre and are easier and faster to deploy, but often have lower resilience than the wired counterpart [18]. Copper-based last mile connections are widely available, highly reliable and cost effective, however, even the state-of-the-art digital subscriber line technology fails to meet fibre-like data speeds [19]. A heterogeneous backhaul network with diverse capabilities and constraints is, therefore, unavoidable and perhaps favourable for the launch of 5G services [20].

At the same time, the RAN is also migrating toward a heterogeneous network composed of a large range of cell sizes (defined by transmit power and antenna height), radio access technologies, and advanced features (e.g., CoMP, data/control plane separation, carrier aggregation, etc.). Moreover, C-RAN, F-RAN, and traditional RAN will also co-exist in the same network. The end result is an abundance of radio cells with diverse capabilities, constraints, and requirements.

On the other hand, eight 5G service use-case families have been identified, "ranging from delay-sensitive video applications to ultra-low latency, from high-speed entertainment applications in a vehicle to mobility on demand for connected objects, and from best effort applications to reliable and ultra-reliable ones such as health and safety" [21]. Moreover, these services will be delivered across a wide range of devices with different capabilities in caching, processing, signal amplification, MIMO, and battery-life. Consequently, even from the users' point of view, each has access to a diverse spectrum of stipulated QoE, constraints and capabilities governed by the device, the application, and the user's profile.

Consequently, optimising NGMNs is greatly more complex than optimising incumbent networks due to the increasing diversity aspect in all its sections: backhaul, radio, and end users. NGMNs network operators are concerned with one prime objective: maximise their revenue. To this end they need to maximise the users' satisfaction to increase their market share while minimising the network expenditure. In incumbent networks, the radio access is the main bottleneck and the main optimisation focus. NGMN optimisation is integrally different with broader possibilities which could be seen as extra challenges but, alternatively, they could also be exploited and converted into opportunities. To this end, network optimisation has become an end-to-end endeavour in which joint RAN/BH operation plays a central role.

B. The user-centric-backhaul: a joint RAN/BH optimisation scheme

We have demonstrated that the users accessing an NGMN are diverse in their respective devices' capabilities, applications' attributes, mobility, priority, and their preferences in ranking different network aspects such as cost, speed, reliability, etc. Moreover, there are numerous candidate cells for users to connect to at any point and more options to backhaul to the core network. An optimised network operation entails intelligent user-cell-backhaul associations that maximise the utilisation efficiency of the network in parallel with users' QoE, as a first goal. When it is no more possible to maintain users' QoE with the given infrastructure, network expenditure should be considered in an optimised manner. Hence, the optimised network operation should highlight the areas that require upgrades with the least cost but highest pertinent gain to enable cost-effective network expenditure. The traditional association scheme that is based on radio signal strength is obsolete and needs to be replaced with a mechanism that captures the diversity of the problem and benefits from the heterogeneity of the network. Moreover, in view of the explosive spread of small cells which increases the complexity of the optimisation problem, and the need for fast adaptability to dynamic network conditions and users behaviour, it is essential to employ distributed self optimised network (SON) techniques to manage this matching exercise

The UCB is a multiple attribute decision making scheme that uses distributed SON techniques to influence users cell selection in a BH-aware, user-QoE-aware, and radio-aware manner. In the UCB, the radio cells have knowledge of the dynamic status and capabilities of their connected backhaul links and the corresponding radio channels. They employ this information jointly to optimise a set of offset factors that reflect the different end-to-end cell constraints/capabilities. A high capacity-based offset indicates that the cell is capable of ensuring end-to-end high capacity to potential users, whereas a low latency-based offset is associated with high end-to-end latency, thus, discouraging users with stringent delay requirements. Similarly, a low resilience-based offset indicates that the cell has high outage probability, due to weather-dependant wireless backhaul link, for instance. Other offset values may correspond to the level of energy efficiency, cost per bit, relative security, etc. On the other hand, users have relative weights to different QoEs, affected by the device capabilities, the user preferences, and the application used. With diligent settings of these offsets, it is possible to optimise the user-cell-BH matching exercise in a way that satisfies the users' QoE while respecting the network's conditions. This leads to a user-centric virtual perspective of the network cells' footprints, tailored to each user's needs.

1) Network performance: A case study using the UCB is presented in [22] in which three quality aspects are jointly optimised: data rate, latency, and resilience. Small cells in a heterogeneous network are randomly allocated different types of BH solutions, each with corresponding capabilities and constraints. In parallel, users are spread randomly in the network and each is allocated random performance targets and weights toward each of these quality aspects. The small cells dynamically optimise their broadcast offset values (three offsets) in such a way that they achieve the maximum throughput on the backhaul without degrading the quality perceived by the users. The performance of the UCB is compared to the state-of-the-art (Fixed CREO) user-cell association that uses a common fixed offset value for all small cells. The cumulative achieved throughput in the network and the number of users in outage are shown in Figure 1 and represent the key performance indicators (KPI) from the network's point of view. A minor degradation in network KPIs is measured in comparison with the Fixed CREO; 3.3% and 6.5% in throughput and users in outage, respectively.

2) Users' perceived performance: The same study looks at the users' KPIs which is represented by a novel metric that measures the gap between the target and achieved performance as a percentage of the target. For instance, a user with a target data rate of 1 Mbps and achieved data rate of 0.9 Mbps is associated a metric of 10%. Similar metrics are computed for the three quality aspects and for all the scenarios simulated;

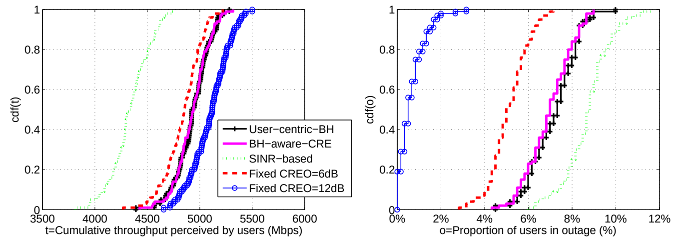

Fig. 1. (Left) Cumulative users' throughput: CRE-based schemes outperform the SINR-based scheme and the novel User-centric-BH lags behind the maximum throughput scheme by 3.3$. (Right) Proportion of users in outage: 6.5% more users are in outage with novel scheme [22].

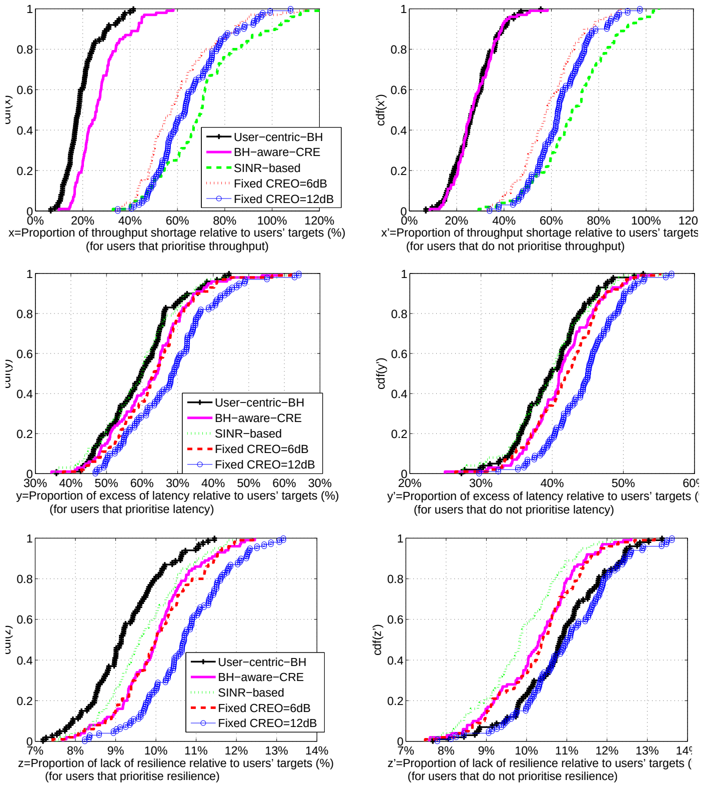

Fig. 2. User-centric KPI measuring the shortage or excess of measured QoE relative to user defined target for: throughput (x,x'), latency (y,y'), and Resilience (z,z'). The left-side figures show the QoE gap of users that prioritise the indicated QoE; the right-side figures show the QoE gap of those who do not prioritise the indicated QoE. The novel approach is the only one that distinguishes users' priorities and outperforms all others in terms of user-centric KPIs [22].

the results are shown in Figure 2. The UCB succeeds in improving users QoE on all targets: throughput (70%), latency (9.6%), and resilience (14.2%) when compared to the maximum throughput delivering scheme (Fixed CREO). Moreover, the UCB proves to be sensitive to users preferences, hence results in an efficient resource allocation that satisfies diverse users needs while simultaneously maximising the networks performance, as seen when comparing the UCB gain in the right graphs to that in the left graphs in Figure 2. From a different angle, the insights drawn from the achievable metrics with the UCB are critical for operators to plan the network optimisation manoeuvres. The UCB allows operators to focus the spending on key network aspects that would unlock the users perceived QoE. Such a joint RAN/BH approach distinguishes the performance gaps due to resources mismanagement from those that cannot be circumvented by intelligent user-cell-backhaul association, hence reveals the hard limits of the network.

3) Energy efficiency: An energy-efficient UCB scheme (EE-UCB) is proposed in [23] and a test-case assuming a Manhattan-grid ultra-dense-network of small cells is considered. Each cell has two optional wireless last mile backhaul links: microwave (high resilience and low capacity) and millimetre wave (low resilience and high capacity). The EE-UCB is composed of two SON processes that interact: (i) The centralised SON located at the backhaul aggregation node and (ii) The distributed SON located in each radio cell. Based on network's and users KPIs, the centralised SON will decide on triggering ON or OFF the last-mile links of each connected small cell. It uses the sliding window technique to avoid ping-pong effect and ensure system stability. The distributed SON uses the basic UCB to adjust the advertised offset values based on the changing capabilities of the last mile. The EE-UCB scheme succeeds in improving the energy efficiency by up to 21.9% at the cost of small degradation in KPIs (both network's KPI and users' KPI), as shown in Figure 3.

C. Cost versus benefit of F-RAN from a joint RAN/BH perspective

A case-study-based analysis of the tradeoff of cost-versus-benefit of different F-RAN architectures and BH technologies is presented in [24]. The study takes on a joint RAN/BH perspective and is based on a holistic network dimensioning method using the UCB scheme. Research on the "C-RAN versus traditional RAN" dilemma often advocate C-RAN for its superior RAN functionality, increased resource utilisation efficiency, greener operation and significant RAN cost reduction. Nonetheless, these benefits are met with stringent fronthaul performance requirements, hence, C-RAN is only feasible with a fibre-based fronthaul which is often unavailable and very expensive and impractical to deploy. On the other hand, there are studies that promote traditional RAN because it operates over a realistic BH, but warns against losing the centralisation benefits. Various functional splits (F-RAN options) are also analysed from a fronthaul perspective and resulting reduction in overhead, while highlighting the increase in RRU complexity and the incurred limitation in RAN features. Table I summarises the general messages from the C-RAN/traditional-RAN comparison. Contrary to the common belief, the C-RAN with fibre fronthaul is shown to be the most cost effective solution from a joint RAN/BH perspective. It come as a results of the advantage of RAN centralisation for reducing the RAN cost, on one hand, and the ability of fibre to allow a significant increase in throughput. As such, although fibre BH incurs the highest total cost of ownership, the associate gain pays-off when the trade-off is analysed over 10 years. However, the cost factor related to the inconvenience of trenching and associated indirect expenditures are not accounted for in this study. Moreover, novel wireless solutions, such as in-band beamforming BH and/or emerging extremely high frequency BH, are not explored and may offer other perspectives into the benefits of alternative F-RAN architectures.

TABLE I
COMPARISON BETWEEN D-RAN AND C-RAN ARCHITECTURES [24].

Factor	D-RAN	C-RAN
Cost of RRU / small cell	High	Low
Planning, deployment, maintenance of RRU	High	Low
Energy efficiency of RRU	Low	High
Cost of BBU	N/A	High
Planning, deployment, maintenance of BBU	N/A	Low§
Energy efficiency of BBU	N/A	High
Potential for resource pooling	Limited	High
Fronthaul requirements	Relaxed	Exigent
Cost of backhaul/fronthaul	High	Higher
Level of inter-cell coordination	Limited	Maximum

The study also highlights the key role of a heterogeneous backhaul/fronthaul in catering for different small cell needs during the early phases of NGMN deployment. The benefits of heterogeneity, however, can only be fully reaped by enabling joint RAN/BH design, operation, and optimisation.

IV. CONCLUSION

In this work, we investigate the central role of joint RAN/BH optimisation as a key enabler to next generation mobile networks. We provide a survey of the state-of-the-art advances in this domain and explore the challenges of optimising future networks. We demonstrate how joint RAN/BH optimisation can be employed to convert these challenges into opportunities for unlocking the performance of future networks despite the realistic constraints inherited from incumbent networks. To this end, the benefits of the user-centric-backhaul scheme are explored from different perspectives. First, we show its potential in ameliorating users satisfaction without necessitating infrastructure upgrades. Second, the possibility of optimising the energy consumption, in addition to network and users performance, is also validated. Last, the scheme is used to conduct a cost-versus-benefit analysis of different radio access network architectures.

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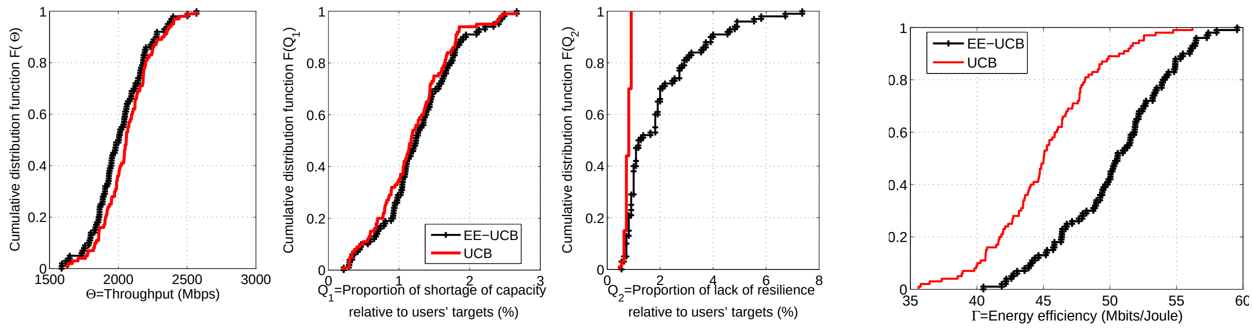

Fig. 3. The left=most figure shows the cumulative system application-layer throughput. The second figure shows the gap between the users' required and achieved throughput. The third figure shows the difference between required and achieved latency. The rightmost figure shows the cumulative distribution function of energy efficiency for both schemes over the 100 runs [23].

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